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**SWITCHING ZONE CONTROL AS
A DISTRIBUTED CONTROLLER**

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report investigates the use of switching zone control (SZC) to control a multidegree of freedom robotic mechanism. Two powerful attributes of switching zone control are decentralization and near minimum time. The "decentralized" property allows the use of a distributed control system where each motor/joint of a multilink mechanism is independently controlled, for example, by its own microprocessor. Overall control can also be accomplished with another microprocessor which would coordinate overall motions and (CONT'D ON REVERSE)		

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communications. The coupling effects from other links and motors as well as random valued gravity and friction effects are handled as disturbing torques. The newly investigated work reported here deals with: (1) experimental results and verification of applying SZC to a multidegree of freedom robotic system; (2) real-time identification of gravity, friction, and other effects to adaptively compensate for nonzero steady-state disturbing torques; and (3) extension of SZC to systems with elastic joints.

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TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
SWITCHING ZONE CONTROL	2
CONTROL OF A PANTOGRAPH ROBOT	6
SYSTEM WITH ELASTIC JOINT	9
NONZERO STEADY-STATE DISTURBING TORQUE	9
SUMMARY AND CONCLUSIONS	10
REFERENCES	12

LIST OF ILLUSTRATIONS

1. Block diagram of switching zone control system	4
2. Phase diagram for switching zone control system using typical trajectory	6
3. Pantograph robot showing vertical plane x-y motors and linkages	7
4. Link angles x and y and corresponding motor torques U_x and U_y	8

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INTRODUCTION

Switching zone control (SZC) is a nonlinear feedback controller with the following characteristics (refs 1-5): (1) decentralized control; (2) near minimum time which approaches the bang-bang minimum time controller in the limit; (3) designer-specified peak torques for a given motor which solve the saturation problem; (4) designer-specified maximum velocity, for example, when the motors have limited horsepower; and (5) easy programming using digital microprocessors. The basis of SZC is the time optimal bang-bang theory where maximum effort is applied by motors in both negative and positive directions (accelerating and decelerating phases) to move a mechanism from one state to another in minimum time (refs 1-3). Instead of a switching boundary as used in the bang-bang approach, a switching zone is used whereby the torque varies linearly. Outside this zone, the torque takes on the maximum allowable values as in bang-bang. Finally, since peak torques are prespecified, SZC eliminates the usual problems of overshoot and relative instability inherent in high gain linear feedback systems where saturation of motors and/or amplifiers becomes a problem.

To date, verification of theoretical results for SZC has been primarily by simulations. This report presents experimental results of applying SZC to two degrees of freedom of a three-degree of freedom pantograph robot. Results obtained confirm the minimum time aspects of a multidegree of freedom SZC without instability or overshoot. Coupling terms were effectively handled as disturbing torques. Robustness was also verified by artificially introducing errors in the form of time delays and/or parameter inaccuracies with resulting minimal effect on desired trajectories and times of operation.

References are listed at the end of this report.

In the derivation of SZC, it was assumed that the disturbing torque was zero in the steady-state limit. This is generally not the case where gravity, friction, and other effects could be nonzero and unknown. The method used most successfully to handle this problem was to compute the real-time feedforward term that automatically cancels any steady-state torques present. This was done by computing the work performed in real time and comparing it to momentum changes.

Finally, SZC was extended to a mechanical system with elastic joints (ref 5). The elastic joint is the simplest idealization of the flexible/compliant robotic mechanism. Reference 5 contains details of the control of a motor operating through a flexible coupling and solutions to both the stability and controller design problems for the elastic joint case.

SWITCHING ZONE CONTROL

Xia and Chang (ref 1) presented in detail some of the modifications to the bang-bang control theory necessary for SZC. They proposed controlling each link or degree of freedom of a robotic system in a decentralized fashion. Instead of a switching boundary as used in the bang-bang approach, a switching zone is used whereby the torque varies linearly. Outside this zone, the torque takes on the maximum allowable values as in bang-bang. In addition, the decelerating phase starts at a lower value of speed so that only a fraction of the available torque is needed to guide the system along its decelerating trajectory without overshoot.

Equation (1) shows a simple second order system where all of the inter-linking coupling terms of a multilink system, as well as gravity and friction effects, are considered as a single disturbing force, u_{di} :

$$J_i \ddot{\theta} = u_{di}(\theta, \dot{\theta}, \ddot{\theta}) + u_i \quad (1)$$

where

J_i = inertia of the i th link

θ_i = angular position of the i th link

u_i = motor torque at the i th link

u_{di} = disturbing torque which includes Coriolis, centrifugal, gravity, and friction coupling effects

$(\underline{\theta}, \underline{\dot{\theta}}, \underline{\ddot{\theta}})$ = vectors of position, velocity, and acceleration for a multilink system

A schematic diagram of the nonlinear switching zone controller for a typical link is shown in Figure 1 where the subscript i has been dropped. The "plant" in Figure 1 can be the simple second order system given as Eq. (1) or a more complicated plant including, for example, elastic joints (ref 5). The variables θ_r and $\dot{\theta}_r$ in the figure are the desired reference angle and velocity; e and \dot{e} are the error functions; and the nonlinear blocks N_1 , N_2 , N_3 , and N_4 are defined as follows (ξ = input variable, η = output variable):

$$\begin{aligned} \eta &= k_1 \xi \quad \text{for } |\xi| \leq u_m/k_1 \\ N_1: \quad \eta &= u_m \quad \text{for } \xi > u_m/k_1 \\ \eta &= -u_m \quad \text{for } \xi < -u_m/k_1 \end{aligned} \quad (2)$$

$$N_2: \quad \eta = \frac{J_m}{2au_m} |\xi| \xi \quad (3)$$

$$\begin{aligned} \eta &= k_2 \xi \quad \text{for } |\xi| \leq b/k_2 \\ N_3: \quad \eta &= b \quad \text{for } \xi > b/k_2 \\ \eta &= -b \quad \text{for } \xi < -b/k_2 \end{aligned} \quad (4)$$

$$\begin{aligned} \eta &= 0 \quad \text{for } |\xi| \leq v_m \\ N_4: \quad \eta &= V(\xi - v_m) \quad \text{for } \xi > v_m \\ \eta &= V(\xi + v_m) \quad \text{for } \xi < -v_m \end{aligned} \quad (5)$$

where

$$\lambda_1 = \frac{k_1 k_2 + \sqrt{(k_1 k_2)^2 - 4k_1 J}}{2J} \quad (8)$$

v_m = maximum allowable velocity

V = constant chosen to smoothly maintain maximum velocity near v_m

k_1, k_2 = proportional and velocity gains where

$k_2 \geq 2\sqrt{J/k_1}$ is required for no overshoot

The maximum torque u_m can be specified arbitrarily or can be fixed based on the motor/amplifier specifications. The gain k_1 is fixed high and is limited primarily by the requirement for no system chatter/jitters, which are common effects in pure bang-bang control. Infinite gain k_1 reduces the control to switching boundary or bang-bang.

A better understanding of the characteristics of SZC can be obtained by examining the resulting phase diagram for the second order system. Figure 2 is a plot of $\dot{\theta}$ versus θ where u_d in Eq. (1) is assumed to be zero. The system with nonzero u_d is considered later in this report. The controller in this case is designed to drive any given nonzero state toward the origin. For example, if the initial state in Figure 2 starts at point A, maximum torque $u = u_m$ is applied at first. The path then eventually enters the zone between full negative and positive torques. Once in the zone, the state is captured and is driven to the origin with little or no overshoot (see Reference 1 for details). Xia and Chang (ref 1) and Jeng (ref 2), as well as these investigators (ref 5) have found this approach to be very effective, even in the presence of minor time delays and parameter inaccuracies.

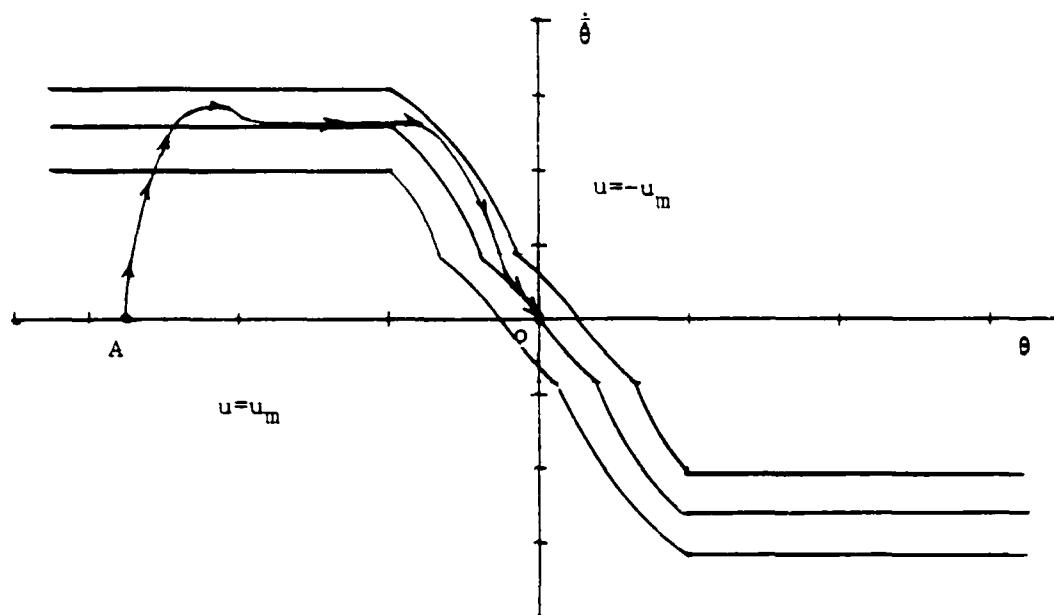


Figure 2. Phase diagram for switching zone control system using typical trajectory.

CONTROL OF A PANTOGRAPH ROBOT

The SZC method was applied to a laboratory pantograph robot as shown in Figure 3. This robot has three primary degrees of freedom. One degree of freedom is in the waist which allows limited motion of the robot about a vertical axis. The other two degrees of freedom allow motion in a two-dimensional vertical plane. The linkage for these two degrees of freedom has characteristics of a pantograph drafting instrument where motion is actuated through two separate sides of a parallel framework as shown in Figure 3.

A switching zone controller was implemented for the pantograph robot using developed software on a Zenith personal computer and Data Translation A/D and D/A computer boards. Feedback was achieved using encoders where velocity was calculated using consecutive positional information. Sampling times used were of the order of 10 milliseconds.

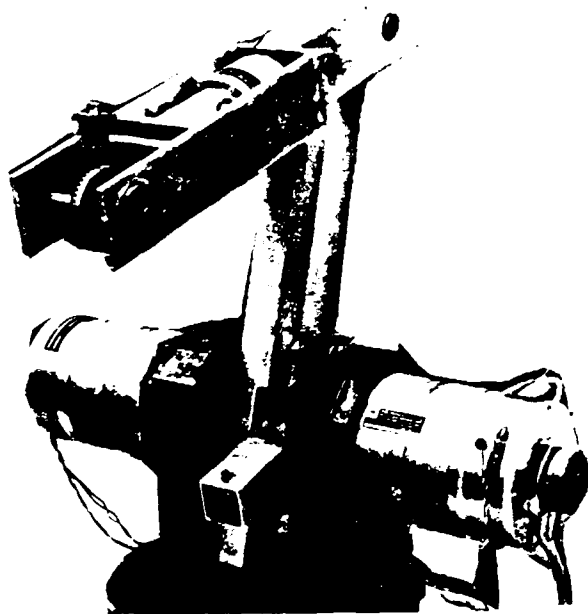


Figure 3. Pantograph robot showing vertical plane x-y motors and linkages.

Numerous trials were conducted to test SZC. The nominal values of SZC parameters for the two degrees of freedom (x and y coordinates) used for these trials are given as follows:

$$\begin{aligned}
 J_{mx} &= 100.0 \text{ in.-lbs/rad/sec}^2 \\
 J_{my} &= 50.0 \text{ in.-lbs/rad/sec}^2 \\
 u_{mx} &= u_{my} = 600.0 \text{ in.-lbs} \\
 v_{\max} &= 100 \text{ to } 150 \text{ degrees/sec} \\
 a &= 0.8 \text{ to } 1.0 \\
 b &= 0.09 \\
 k_{1x} &= k_{1y} = 7000.0 \text{ in.-lbs/rad} \\
 k_{2x} &= 0.12 \text{ in.-lbs/rad/sec} \\
 k_{2y} &= 0.09 \text{ in.-lbs/rad/sec}
 \end{aligned}$$

The velocity gains k_{2x} and k_{2y} as given above are about half the values that were calculated using Eq. (8). This prevented chattering of the mechanism resulting from the relatively long sampling interval of 10 milliseconds along with inaccurate velocity calculations that were used.

Small additional time delays of the order of 10 milliseconds along with variations of the order of 10 to 20 percent in the nominal parameters given above were also made to test the robustness of SZC. Highly satisfactory results were obtained in all instances and all runs were stable with little or no overshoot. An example of the results is shown in Figure 4 for (x,y) motions for SZC parameters. Stable motion is observed with no overshoot, although the torque plots show considerable variations.

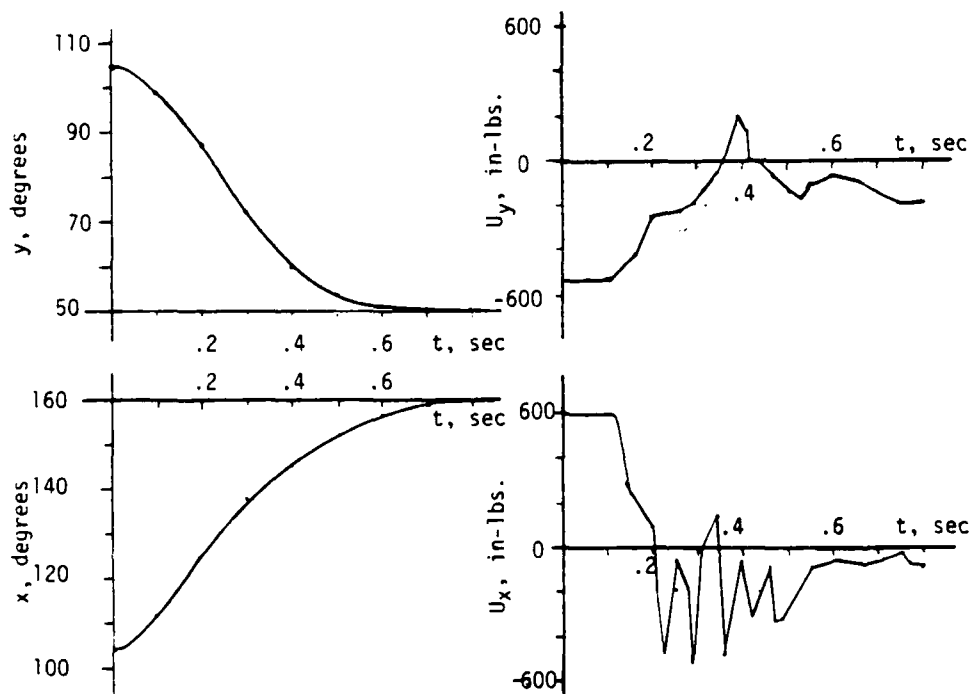


Figure 4. Link angles x and y (degrees) and corresponding motor torques U_x and U_y (in.-lbs.).

SYSTEM WITH ELASTIC JOINT

The ramifications of including an elastic joint between the motor and the payload on the design of a switching zone controller were considered in Reference 5. This is perhaps the simplest case of the compliant/flexible manipulator. There is considerable interest at the present time in controlling lightweight, flexible mechanical systems, particularly in nonindustrial applications such as space or military where weight and speed of operation are critical factors. The totally elastic or flexible arm is an infinite degree of freedom system which, in the simplest idealization, reduces to a fourth order spring-mass system.

In general, the closed-loop linear feedback for this case using only endpoint information is unstable. In order to assure stability, co-located motor velocity feedback is required in addition to endpoint (payload) position and velocity feedback. This case is briefly mentioned here to indicate the versatility of the approach in practical situations. Further details can be found in Reference 5.

NONZERO STEADY-STATE DISTURBING TORQUE

In the derivation of SZC it was assumed that the disturbing torque u_d was zero in the limit. This is generally not the case where gravity, friction, and other effects result in nonzero steady-state disturbances. Consequently, steady-state motor torques are required to overcome these disturbances in order to maintain a desired payload or mechanism position or state. However, the disturbing torque cannot be predicted beforehand since friction effects vary from cycle to cycle and unknown gravity effects may be present. The nonpredict-

ability of the gravity effects is especially true when the payload varies in a random fashion or when a mechanism is placed on a moving vehicle where orientation varies.

The most successful and easiest approach used in these studies was to compute the real-time feedforward term that automatically cancels any steady-state disturbing torques present. An efficient way of accomplishing this is to compute both the work performed by the motor and the momentum change over a short period of time. Integrating Eq. (1) over a small time interval (t_0, t) gives

$$J(\dot{\theta}(t) - \dot{\theta}(t_0)) = \int_{t_0}^t u(t)dt + \bar{u}_d * (t-t_0) \quad (9)$$

in which \bar{u}_d is an approximate average value of the disturbing torque over the time interval $\Delta t = (t-t_0)$. Solving for \bar{u}_d yields

$$\bar{u}_d = (J(\dot{\theta}(t) - \dot{\theta}(t_0)) - \int_{t_0}^t u(t)dt)/\Delta t \quad (10)$$

The quantities on the right-hand side of Eq. (10) are known or can be computed in real time and consequently \bar{u}_d can be calculated in real time. A feedforward term can then be added directly to the input for the motor, effectively counterbalancing steady-state disturbances in real time.

SUMMARY AND CONCLUSIONS

Basically, a control procedure was presented for independently applying SZC to each link of a multidegree of freedom system. Experimental results described herein have demonstrated the decentralized nature of SZC along with other desirable attributes such as near minimum time, stability, and no overshoot. Real-time identification of gravity, friction, and other effects was also considered for adaptively compensating for nonzero steady-state disturbing torques.

Switching zone control, as outlined in this report, has been applied to Army subsystems being developed at Benet Laboratories. It is proving to be a very effective means of controlling mechanisms where the exact path following is not required and minimum time is the more desirable objective.

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